IV. Cosmology

- Lookback time
  - Farther away = seeing farther back in time
  - Questions about galaxy evolution (ellipticals, spirals, etc.)
  - c = 1 light-year / year
- A Uniform Expansion
  - Same expansion rate everywhere
  - Models : paperclips on rubberband, pennies on baloon, the Universe...
- Expansion timescale
  - The “Hubble Time” t_H
  - How old the expansion would be *if the expansion rate had always been constant*.
  - $\frac{\Delta d}{d} = \frac{\Delta t}{t_H}$

IV. Cosmology (continued)

- Cosmological redshift
  - Wavelengths of light stretch at the same rate as the expansion of the Universe.
  - $z = \frac{\Delta d}{d}$ $\quad 1+z = \frac{\text{Size Now}}{\text{Size then}}$
- The expansion equation
  - $z = \frac{d}{c\, t_H}$ $\quad$ our t_H = 13.8 Gyr
- Evidence for Dark Matter
  - Galaxy Rotation Curves
  - Galaxy cluster random motions
  - Most of the matter offset from the luminous matter as measured in the Bullet Cluster with “weak lensing”

IV. Cosmology (continued)

- Measuring Distances
  - Cosmic Distance Ladder
  - Parallax
  - Standard Candle : Cepheid Variable
  - Standard Candle : Type Ia Supernova
- The Hubble Diagram
  - Plot of size (measured by redshift) vs. time (measured by distance/lookback time/brightness of standard candle)
  - Where is t_H
  - Accelerating vs. decelerating, age of Universe vs. t_H, etc.

IV. Cosmology (continued)

- Constituents of the Universe
  - Dark Energy (70%) : drives acceleration
  - Dark Matter (25%) : holds galaxies, clusters together, has normal gravity
  - Normal Matter : makes up stars, dust, gas, us, everything we can directly see
- Evidence for the Big Bang
  - Expansion / Cosmological Redshift
  - Cosmic Microwave Background
  - Ratios of the light elements
- Calculating expansion history
  - General Relativity + (reasonable, tested) assumption of homogeneous & isotropic
  - 3 parmaeters: t_H (today's expansion rate), Ω_M (matter density), Ω_Λ (dark energy density)

(Drumroll please...)

The Age of the Universe:

13.7±0.2 billion years

...but what is that since?

...clips from a movie:

From Here to Infinity:
How Will the Universe DIe?

Prof. Knop, helping to discover the acceleration of the Universe.

(Shown as part of the BBC “Horizon” series in 1999.)